PB-236 265

EVAPCRATION FROM LAKE MICHIE, NORTH CAROLINA, 1961-71

W. L. Yonts, et al

Geological Survey

Prepared for:

North Carolina Board of Water and Air Resources

August 1973

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

IBLIOGRAPHIC DATA HEET

1. Report No. USGS-WRD-74-031

2.

PB 236 265

Title and Subtitle

Evaporation from Lake Michie, North Carolina 1961-71

5. Report Date August 1973

6.

Author(s) W. L. Yonts, G. L. Giese, and E. F. Hubbard

8. Performing Organization Rept. No. WRI 38-73

Performing Organization Name and Address

U. S. Geological Survey
Post Office Box 2857
Raleigh, North Carolina

10. Project/Task/Work Unit No.

11. Contract/Grant No.

Sponsoring Organization Name and Address

U. S. Geological Survey
Post Office Box 2857
Raleigh, North Carolina 27602

13. Type of Report & Period Covered

Final

14.

Supplementary Notes

Prepared in cooperation with the city of Durham, North Carolina

Abstracts

Evaporation data was collected at Durham's 480-acre water-supply reservoir for 10 consecutive years. Wind speed, air temperature, and water temperature--measured continuously--were used in conjunction with water-budget data to calibrate the semi-empirical mass-transfer equation.

Frequency curves of maximum net evaporation reveal that net evaporation is a significant factor in the design and management of reservoirs. For example, over 14.5 inches of net evaporation from Lake Michie may be expected to occur during a 6-month period on an average of once every 20 years.

Relations derived from the evaporation data provide a means for predicting the evaporation loss from a reservoir in the Piedmont area of North Carolina, allowing the user to compensate for the loss when designing a reservoir.

Key Words and Document Analysis. 17a. Descriptors

*Reservoir evaporation/ *water loss/ *evaporation pans/ *mass transfer/ *reservoir design/ seepage/ draft-storage curves/ air-water interfaces/ energy budget/ water supply/

b. Identifiers/Open-Ended Terms

Lake Michie/ Neuse River/ Flat River/ mass-transfer water-budget technique/ N coefficient/ G. E. Harbeck/

c. COSATI Field/Group Ø 2D, Ø 6A

Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 33
No restriction on distribution	20. Security Class (This Page) UNCLASSIFIED	22. Price 3.25

EVAPORATION FROM LAKE MICHIE, NORTH CAROLINA 1961-71

By
W. L. Yonts, G. L. Giese, and E. F. Hubbard

U. S. Geological Survey
Water-Resources Investigations 38-73

Prepared in Cooperation with the
City of Durham, North Carolina
1973

UNITED STATES DEPARTMENT OF THE INTERIOR
ROGERS C. B. MORTON, SECRETARY

GEOLOGICAL SURVEY
V. E. McKELVEY, DIRECTOR

CONTENTS

ILLUSTRATIONS

CONTENTS

TABLES

EVAPORATION FROM LAKE MICHIE,

NORTH CAROLINA 1961-71

By W. L. Yonts, G. L. Giese, and E. F. Hubbard

ABSTRACT

The Geological Survey, in cooperation with the city of Durham, N. C., collected evaporation data at Lake Michie, Durham's 480-acre water-supply reservoir, for 10 consecutive years from September 1961 to September 1971. Wind speed, air temperature, and water temperature--collected continuously--were used in conjunction with water-budget data to calibrate the semi-empirical mass-transfer equation, $E = Nu(e_o - e_a)$, where E is evaporation; N is the mass-transfer coefficient, which is a constant for a given lake; u is wind speed; e_o is the vapor pressure of the saturated air at the water surface; and e_a is the vapor pressure of the surrounding air. For evaporation expressed in inches, the mass-transfer coefficient for Lake Michie is 0.0036.

During the study period the average annual evaporation from Lake Michie was 37.9 inches. Within-year variation of evaporation from the lake is sinusoidal, with a high during July averaging 4.71 inches and a low during January averaging 1.45 inches.

Evaporation from Lake Michie was 0.72 (or about three-quarters) of the evaporation from the National Weather Service evaporation pan at Chapel Hill. This ratio, called a pan coefficient, was not constant throughout the year, ranging from an average of 0.57 for April to 1.09 for December.

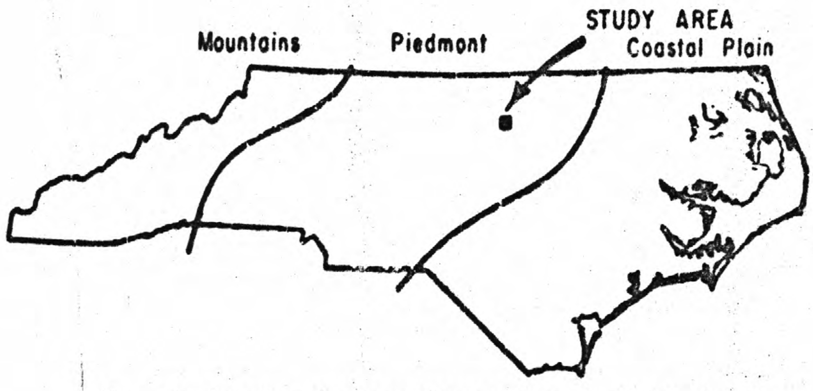
Average annual net evaporation (evaporation minus rainfall) for the study period was -1.02 inches, that is, rainfall exceeded evaporation by 1.02 inches per year. Typically, evaporation exceeds precipitation for the months of April through October and is less for the remainder of the year. Frequency curves of maximum net evaporation reveal that net evaporation is a significant factor in the design and management of reservoirs. For example, over 14.5 inches of net evaporation from Lake Michie may be expected to occur during a 6-month period on an average of once every 20 years.

Relations derived from the evaporation data provide a means for predicting the evaporation loss from a reservoir in the Piedmont area of North Carolina, allowing the user to compensate for the loss when designing a reservoir. For example, a reservoir of 1,000 acres on a stream draining 100 square miles will have an evaporative loss averaging 1.3 million gallons per day during a critical period occurring once every 20 years, on the average.

INTRODUCTION

Previous to this investigation there were no similar long-term studies of monthly reservoir evaporation in the humid southeast, even though evaporation is often an important factor in the availability of water during droughts. It is often assumed that precipitation on a lake or reservoir is about equal to evaporation from the lake surface. While this assumption is a valid approximation on an annual basis in many areas of the southeast, it fails to take into account the strong tendency for periods of maximum net evaporation to coincide with periods of low streamflow. Both of these situations are directly related to deficiencies in rainfall and sometimes combine to create critical water-supply conditions in reservoirs. Thus, there was a need to adequately measure reservoir evaporation on a continual basis for a period of several years so that evaporative losses during critical periods could be properly understood and accounted for in water-supply management and design.

Recognizing this need, the U.S. Geological Survey, in cooperation with the Water Resources Department of the city of Durham, North Carolina, undertook in 1961 an evaporation study of Durham's water-supply reservoir, Lake Michie (see fig. 1), as part of a comprehensive appraisal of the water resources of the upper Neuse River basin. The two primary objectives of the Lake Michie study were to quantitatively determine the evaporation from the lake and to develop and suggest ways to usefully extend the Lake Michie data to other parts of the upper Neuse River basin and to North Carolina. Several approaches to the objective of quantifying Lake Michie evaporation were considered, including the water-budget and energy-budget techniques, pan-to-lake coefficients, and the mass-transfer water-budget technique as described by Harbeck(1962). For reasons of simplicity in application and practicality of field instrumentation, the mass-transfer water-budget technique was chosen as



Map showing the physiographic provinces in North Carolina

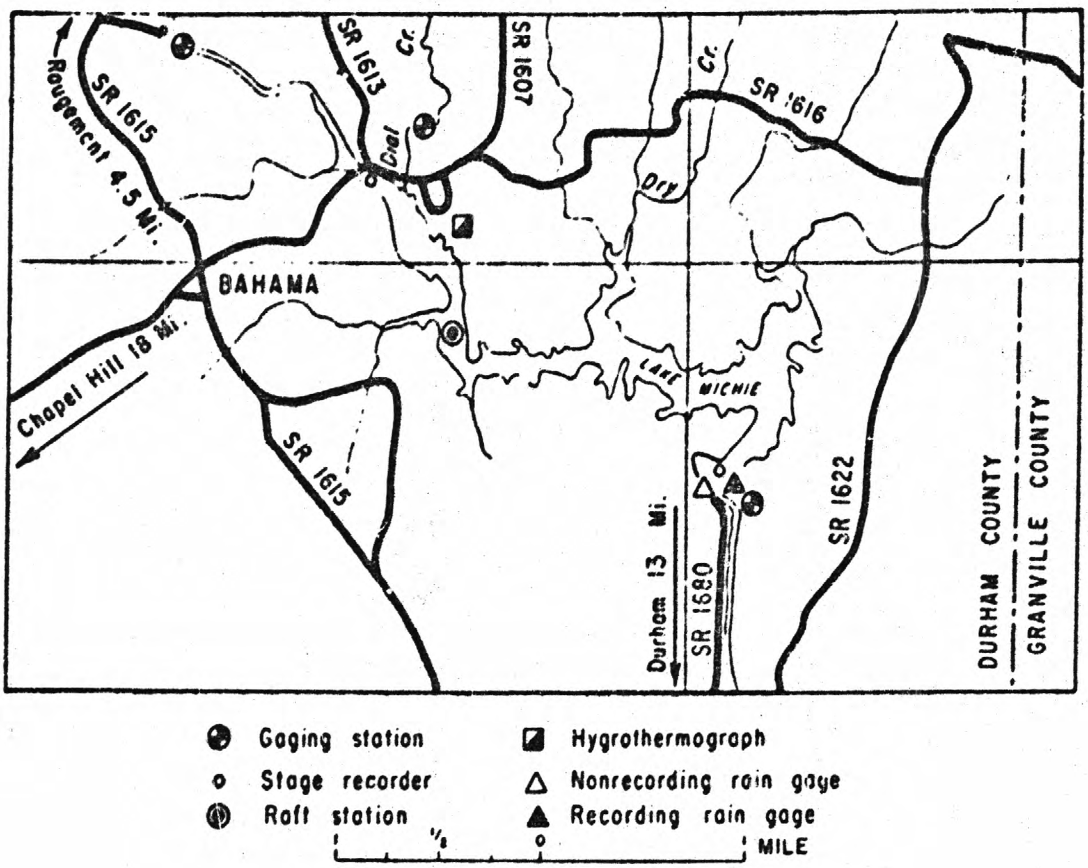


Figure 1.--Location of Lake Michie and instrumentation.

the primary line of approach, and a data-collection program was set up and began operation in October 1961. Data-collection operations continued until September 1971, at which time preparation of this report was begun.

Physical Setting

Lake Michie is an impoundment of the Flat River approximately 13 miles northeast of the city of Durham in north-central North Carolina (fig. 1). The reservoir serves as the water supply for Durham. The drainage area of streams contributing to the lake is approximately 170 square miles, of which the Geological Survey continuously measures streamflow from 155 square miles. The gaging stations, Flat River at Bahama and Dial Creek near Bahama, measure the inflow from 150 and 4.71 square miles, respectively. (See fig. 1.) The lake area at spillway level (altitude is 341 feet above mean sea level) is about 480 acres. Lake volume ranges from about 11,200 to 14,500 acre-feet.

Lake Michie is in a narrow valley bottom with abundant rock outcrops on the medium to steep banks. Average depth of the lake is 30 feet. The maximum depth, from soundings made during the study, is about 70 feet.

The drainage basin is hilly, sparsely populated, and generally wooded with some open farm land. The basin is underlain by granite and granodiorite rocks, with the upper reaches of the basin underlain by metavolcanic rocks.

Streamflow into Lake Michie averages about 170 cfs (cubic feet per second) but during the late summer and early fall, when lake evaporation is maximum, the inflow may be 10 cfs or less.

Climate

The climate of the area is mild and humid. Warm temperatures prevail from May through September with mild to freezing temperatures during the remainder of the year. Freezing weather generally occurs in December and January. Air temperatures in the vicinity of Lake Michie for the period of the study (1961-71) have ranged from an average of 38°F in January to an average of 77°F in July. During the hottest summer days, maximum air temperatures in the afternoon approached or exceeded 100°F.

Mean daily relative humidity generally ranges from 30 to 100 percent and averages about 70 percent.

The average annual precipitation during the study period was 39 inches as compared to the long-term average of 45 inches. Precipitation is fairly evenly distributed throughout the year, but the summer months receive 1 to 2 inches more than the other months. The highest monthly rainfall of 8.2 inches occurred in June 1965 and the lowest monthly rainfall of less than 0.10 inch occurred in September 1968.

Prevailing winds on the lake are southwesterly. Wind velocity for the study period, measured 2 meters (6.5 feet) above the lake surface, averaged 3.2 miles per hour with maximum daily wind velocity of 13.4 miles per hour occurring on November 27, 1962. Minimum daily wind velocity averaged less than 1 mile per hour for many days during the study.

Data Collection

The location of the hydrographic and meteorological data collection sites used in this study are shown in figure 1. The instruments used in the study and the types of data they record are listed in table 1, along with the period of data collection.

As indicated in table 1, the U.S. Geological Survey has measured streamflow into and out of Lake Michie since 1925 and 1927, respectively. The city of Durham has collected lake stage, precipitation, and diversion data for many years. To generate data for application of the mass-transfer water-budget technique, a special raft station (fig. 2) was installed to measure wind movement and water-surface temperatures. Temperature surveys of the entire lake surface indicated that the temperatures at the raft station were representative of water-surface temperatures of the entire lake. With regard to air temperature and relative humidity, it was found that Raleigh-Durham Airport data was representative of Lake Michie and after the first year of the study the weather station at Lake Michie was discontinued.

EVAPORATION OF LAKE MICHIE

Evaporation is the process by which water is changed from the liquid or the solid state into the vapor state. Evaporation requires 597 calories of heat for each gram of water, so that if the surface temperature of a lake is to be maintained, the heat lost must be resupplied to the lake surface either by radiation and conduction from the overlying air or by convection and conduction of heat from the lower levels of the lake. Viewed in this way, as an energy process, solar radiation is the most important single factor controlling evaporation. Being dependent on solar radiation, evaporation varies with time of day, season, latitude, and sky condition. Many other factors--including air and water temperature, vapor pressure, wind, and atmospheric pressure--also influence evaporation rates.

Table 1.--Data used in Lake Michie study

Data collected	Location	Period
Rainfall (non-recording gage)----------------	Dam--------------	1926-.[1]
Do----------------	Near dam---------	September 1926-.[1]
Do----------------	Rougemont (in basin)---------	September 1913-.[1]
Rainfall (recording gage)----------------	Dam--------------	August 1961-.
Inflow----------------	Dial Creek-------	October 1925 - September 1971.
Do----------------	Flat River (upstream from lake)----------	July 1925-.[1]
Outflow----------------	Flat River (downstream from lake)---------	August 1927 - September 1959; August 1961 - September 1966.
Diversion to Durham and Camp Butner[3]---------	Dam--------------	1927-.[1]
Lake stage-------------	Bridge (upstream end of lake)---	August 1961 - September 1966.
Do----------------	Dam--------------	1927 - 1961 (about).
Do----------------	Do----------	August 1961-.
Evaporation-----------	On lake (near dam)-----------	1946 - 61.[1,2]
Do----------------	Chapel Hill	1922-.[1]
Water-surface temperature----------------	Raft station (see fig. 1)---	September 1961 - September 1971.
Air temperature and relative humidity----	Weather station (hygrothermograph of fig. 1)--------	September 1961 - December 1962.
Do----------------	Raleigh-Durham Airport--------	1944-.[1]
Wind speed-------------	Raft station-----	September 1961 - September 1971.

[1]Data collected by other agencies.
[2]Fragmentary.
[3]Diversion to Camp Butner discontinued February 1966.

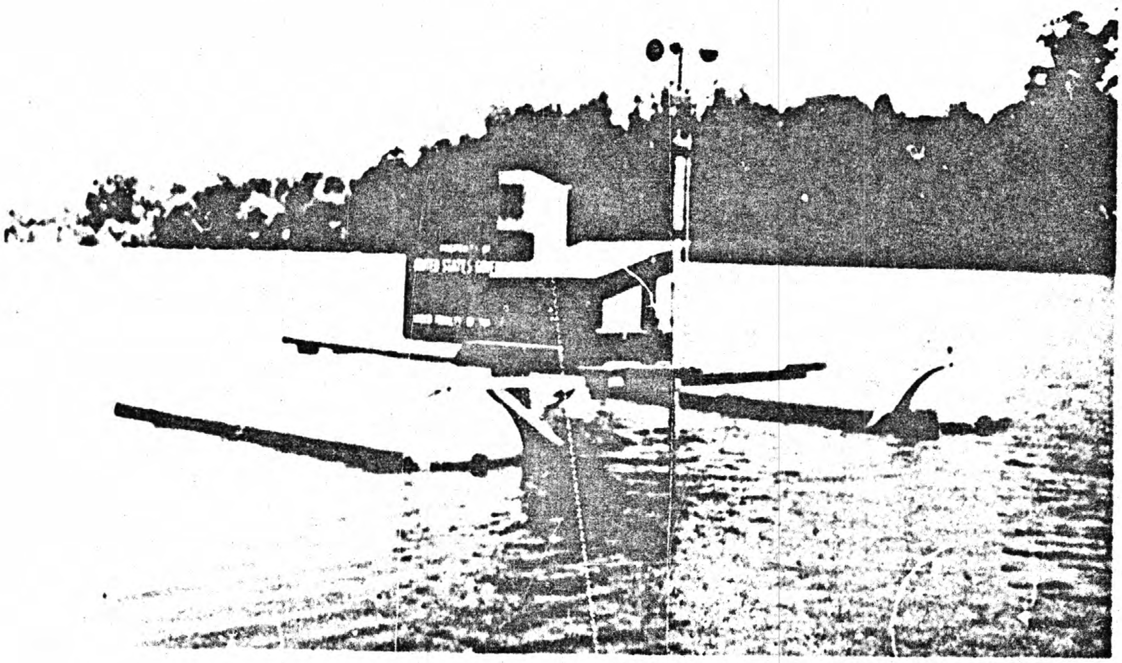


Figure 2.--Lake Michie raft station.

Several approaches to determining Lake Michie evaporation were considered in the early phases of this study, among them correlation of pan evaporation with lake evaporation and the energy-budget, water-budget, and mass-transfer techniques. The method chosen for application to Lake Michie was a quasi-empirical form of the mass-transfer equation as described by Harbeck (1962). Advantages of this method over other alternatives were simplicity of application for Lake Michie, relative accuracy, inexpensiveness of equipment needed, and the ability to make a seepage estimate. (A seepage estimate is important where seepage may be a significant part of the water entering or leaving the lake.)

Application of Mass-Transfer Technique

The mass-transfer equation

The form of the mass-transfer equation used in this report is that described by Harbeck (1962, p. 101-10[illegible]),

$$E = Nu(e_o - e_a) \quad (1)$$

where E is the rate of evaporation, in feet per day; N is the mass-transfer coefficient; u is the wind speed, in miles per hour; e_o is the vapor pressure of saturated air at the temperature of the water surface, in millibars; and e_a is the actual vapor pressure of the air for the existing conditions of humidity and temperature, in millibars.

The use of equation 1 in this study required a simultaneous solution with the simplified water-budget equation (described in greater detail by Turner, 1966, p. 141),

$$\Delta H_A = E + \delta, \text{ or } E = \Delta H_A - \delta \quad (2)$$

where ΔH_A is average change in water-surface elevation adjusted for inflow, outflow (including diversions), and rainfall, in feet per day; E is evaporation, in feet per day; and δ is net ground-water seepage, in feet per day (positive when seepage is from lake to aquifer; and negative, when seepage is from aquifer to lake).

Substitution of E in equation 2 for E in equation 1 yields,

$$\Delta H_A = Nu(e_o - e_a) + \delta \quad (3)$$

Values of ΔH_A were computed for periods where accuracy was maximum; that is, for periods when rainfall was negligible; inflow was small and uniform and outflow was uniform; the so-called mass-transfer product, $u(e_o - e_a)$, was determined from observations of wind speed and water-surface temperatures at the Lake Michie raft station and used in conjunction with air temperatures and relative humidity from the Raleigh-Durham airport.

The mass-transfer coefficient

Knowledge of the mass-transfer coefficient, N, for a lake enables records of evaporation to be generated with the relatively inexpensive equipment needed to determine the mass-transfer product. In the early phases of this study, Turner developed a calibration curve for Lake Michie from which he estimated the mass-transfer coefficient. Calculations based on additional years of evaporation record tend to confirm Turner's original value for N of 0.0036, with evaporation in inches per day, and this value has been used for calculations in this report. The original calibration curve is shown in figure 3.

The mass-transfer coefficient, N, represents the effects of many variables, including the variation of wind with height, lake size and shape, and roughness of the water surface. A relation was developed between lake areas and mass-transfer coefficients for a number of lakes in the United States by Harbeck (1962, p. 104). Lakes used in Harbeck's relation were primarily located in arid or semi-arid climates. When lakes in the humid east are added to the graph, including Lake Michie data, there is no significant difference in the relation (fig. 4). The standard error of estimate in this regression is too large to permit determination of N coefficients by lake areas alone. However, the apparent homogeneity of the data for both humid and arid climates suggests that the coefficient is indeed dependent on the physical characteristics of the lake location, and is relatively independent of climatological differences.

Seepage

One of the advantages of the mass-transfer technique over other methods of determining lake evaporation is that, when surface inflows and outflows can be adequately measured, this method allows an estimate of ground-water seepage into or out of a lake. A negative intercept on the ΔH_A axis of the calibration curve (fig. 3) indicates ground-water inflow to the lake and a positive intercept indicates leakage. The seepage value obtained represents an average value during the months that the calibration was made.

From the calibration curve, we estimated average seepage to be 0.011 foot per day or about 2.75 cfs into the lake during the months of May through November, when the calibration was made. Variation of seepage rates within the May through November period accounts for part of the deviation of the

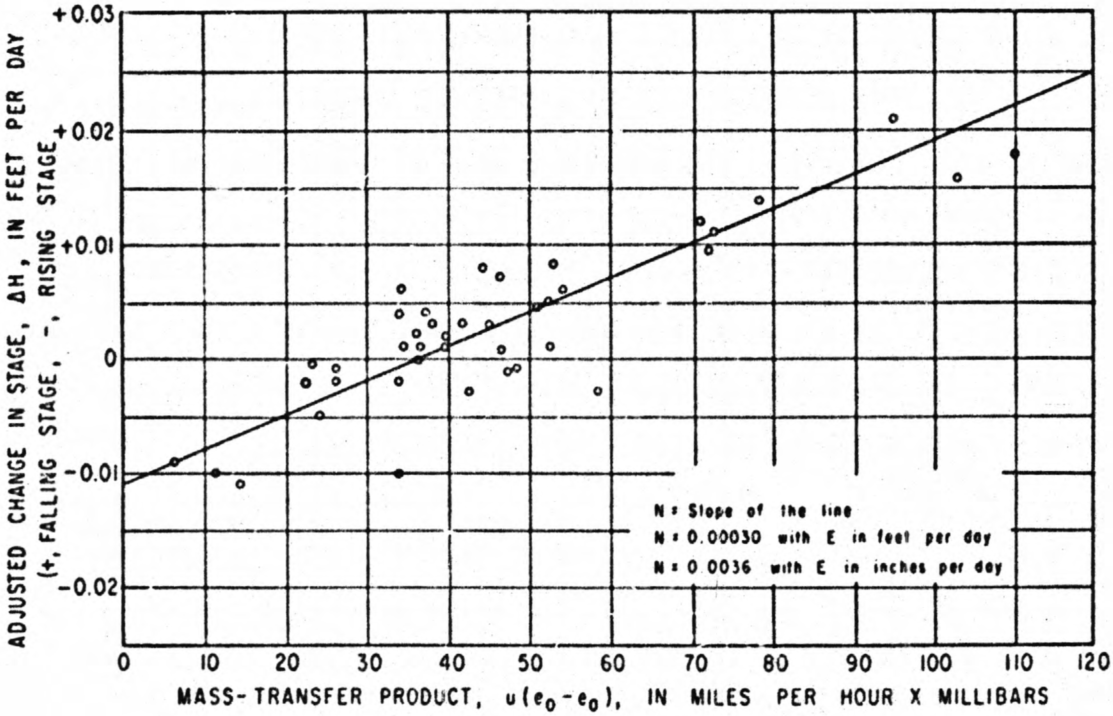


Figure 3.--Calibration curve for Lake Michie.

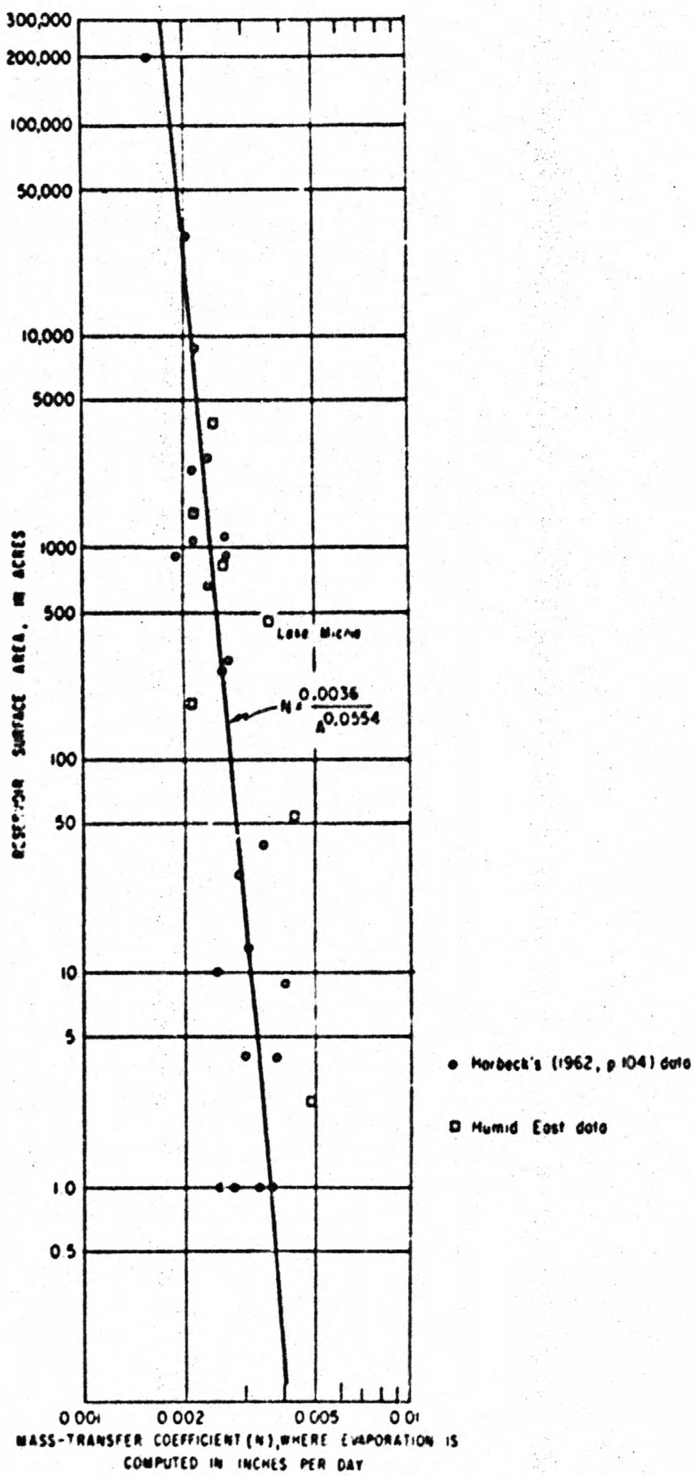


Figure 4.--Relation between mass-transfer coefficient, N, and reservoir surface area.

plotted points from the calibration curve. Seepage rates during the winter months probably average considerably more than 2.75 cfs, and annual net seepage is estimated to be about 5.25 cfs.

For most purposes of Lake Michie management, however, the May through November average seepage estimate of 2.75 cfs is most relevant, particularly because nearly all critical water-supply situations can be expected to occur during these months.

Monthly Evaporation

Monthly evaporation was computed for 1961-71 and the results are presented in table 2. These evaporation data were summarized from daily values of evaporation computed by using the mass-transfer equation, $E = 0.0036\mu(e_o - e_a)$, discussed previously. Monthly values ranged from a minimum of 0.66 inch during January 1962 to a maximum of 7.41 inches for July 1966, while annual values ranged from 30.9 inches in 1967 to 45.4 inches in 1966. The average annual evaporation for the study period was 37.9 inches.

Evaporation is a cyclic phenomenon, as indicated by figure 5, which shows average monthly evaporation for the 10-year study period. Evaporation is cyclic because it varies primarily with available solar radiation, but it also varies with less predictable factors such as cloud cover, wind, relative humidity, and air temperature. These and other factors account for the year to year variations in evaporation for a given month. Usually, however, maximum lake evaporation occurs in July and the minimum occurs in January.

Monthly and annual values of lake evaporation were analyzed statistically to give a measure of the variability from year to year. Table 2 shows the standard deviation of the monthly and annual evaporation from their averages. The standard deviation of February evaporation, for example was ± 0.52 inch. The distribution of the monthly means is approximately normal, so that two-thirds of the monthly values can be expected to fall within the interval of plus or minus one standard deviation from the mean. Thus, for February, approximately two-thirds of the evaporation values would be expected to fall between 1.15 and 2.19 inches. Because evaporation varies primarily with solar radiation in a stable annual cycle, we are confident that the 10-year study period is typical of long-term evaporation. Inspection of the 40-year pan evaporation record at Chapel Hill shows year to year variations in evaporation, but no long-term trends. This gives further assurance of the representativeness of the 10-year study period.

Table 2.--Monthly and annual evaporation for Lake Michie, in inches

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total for year
1961									4.03	3.32	2.65	1.73	-
1962	0.66	1.14	2.59	3.6[illegible]	5.10	5.39	4.85	4.38	3.78	3.58	2.78	3.17	41.1
1963	1.25	2.66	3.01	4.44	4.20	4.32	5.14	5.20	5.02	4.04	2.49	1.87	43.6
1964	1.25	1.41	2.36	2.42	4.50	4.10	4.52	4.05	3.74	2.89	2.34	1.27	34.8
1965	2.27	1.69	1.81	2.50	4.39	4.71	5.17	5.02	4.3[illegible]	4.51	2.30	1.54	40.2
1966	2.17	1.29	3.17	3.77	5.54	6.19	7.41	4.80	4.17	3.36	1.92	1.60	45.4
1967	.76	1.69	1.05	3.78	3.57	3.35	3.56	3.05	3.86	2.62	2.38	1.20	30.9
1968	1.11	2.21	2.41	2.96	3.37	3.39	3.61	5.96	4.01	2.61	1.96	.98	34.6
1969	.91	1.98	2.19	2.26	3.29	3.47	4.73	4.14	3.82	3.31	3.34	3.92	37.4
1970	2.59	1.73	1.54	2.11	4.42	5.95	3.67	3.42	4.09	2.82	2.34	1.88	36.6
1971	1.54	.92	3.04	2.92	3.49	2.61	4.42	4.00	-	-	-	-	34.7[1/]
Monthly and annual average of evaporation	1.45	1.67	2.32	3.08	4.19	4.35	4.71	4.40	4.08	3.31	2.45	1.92	37.9
Standard deviation of monthly and annual values	±0.67	±0.52	±0.69	±0.79	±0.76	±1.20	±1.13	±0.87	±0.38	±0.62	±0.41	±0.92	±4.54

[1/] Includes data from 1961.

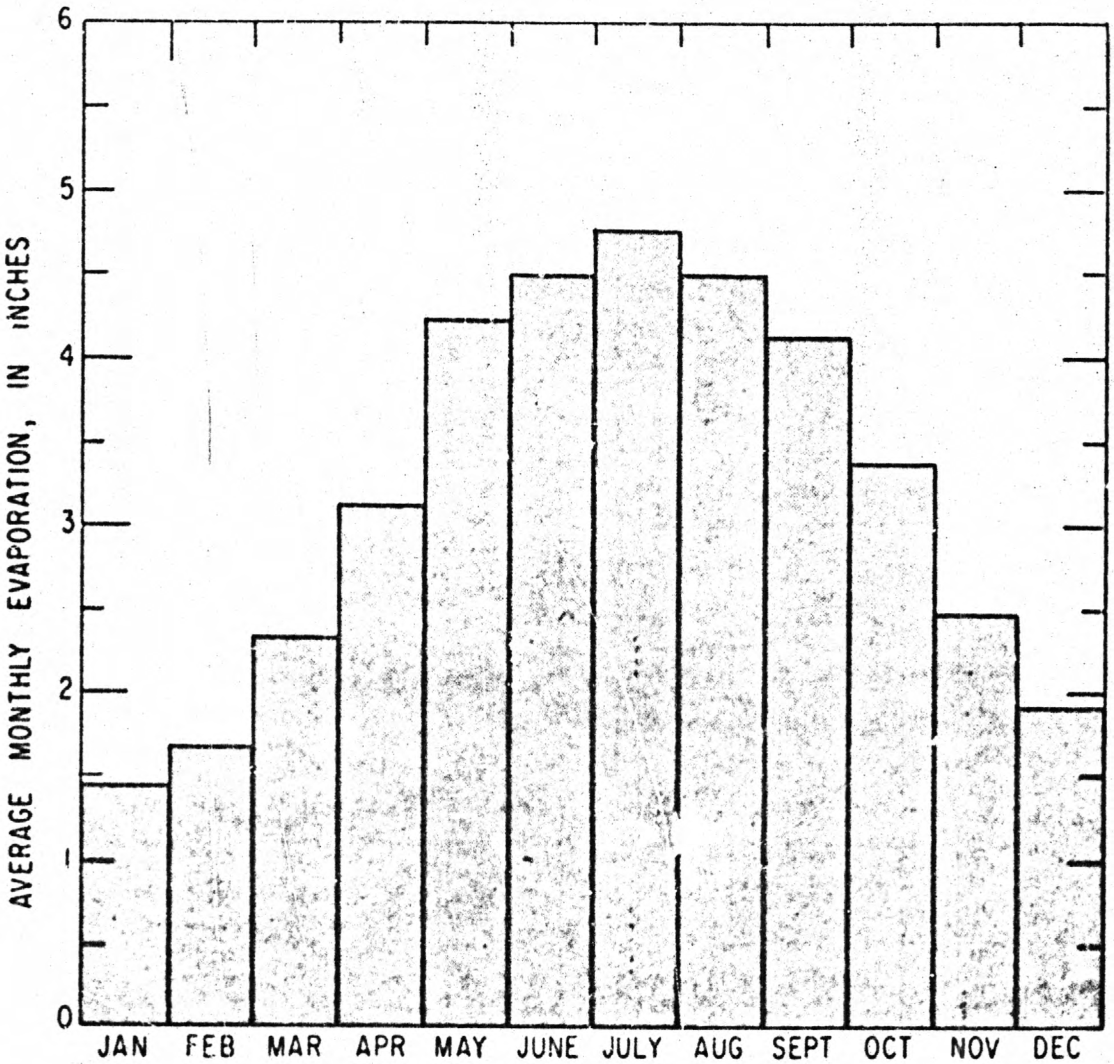


Figure 5.--Average monthly evaporation for Lake Michie, 1961-71.

APPLICATIONS OF LAKE MICHIE EVAPORATION DATA

Comparisons With Pan Evaporation

Comparisons were made between evaporation of Lake Michie and the standard National Weather Service Class A pan at Chapel Hill which is located 18 miles to the southwest. Our object was to establish pan coefficients that could be used to estimate monthly evaporation from lakes where evaporation data have not been collected but for which nearby pan data are available. Monthly and annual pan-to-lake coefficients were computed for the years 1961-71 and are shown in table 3, along with average of the monthly and annual values. The standard deviation of the monthly and annual pan coefficients from their averages are also shown.

The average annual pan coefficient for the 10-year study period was 0.72, which compares closely with pan coefficients determined for other areas in the southeast. This result gives further assurance of the reasonableness of Lake Michie evaporation rates as determined by the mass-transfer technique. For other lakes in North Carolina where no lake evaporation data are being collected, the average monthly pan coefficients for Lake Michie can be applied to nearby pan evaporation data to estimate lake evaporation.

Prediction of Monthly Evaporation

It was found that the 10-year average monthly evaporation as determined by the mass-transfer technique was the best predictor, among several methods tried, of future evaporation rates in that month. A method utilizing current monthly pan evaporation and average pan coefficients for that month proved to be less satisfactory than this method in that the sum of the differences between the predicted and the actual monthly evaporation was greater. Other methods of prediction utilizing serial correlation effects during several months were less satisfactory for the same reason. It is quite possible that additional years of evaporation record would enable a better predictive relation to be defined, but for the present, the 10-year monthly averages of Lake Michie evaporation are the best available indicators of future evaporation in a given month.

Monthly Net Evaporation

For purposes of reservoir management and development it is often more convenient and useful to think in terms of net evaporation, which is the excess of evaporation over rainfall. Monthly precipitation was subtracted from monthly evaporation to obtain monthly net evaporation. The results are shown in table 4. A negative number indicates that precipitation exceeded

Table 3.--Annual and monthly pan-to-lake coefficients from Chapel Hill and Lake Michie for the period 1961-1971

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly
1961									0.92	0.74	1.10	0.93	
1962	0.96	0.53	0.67	0.61	0.65	0.80	0.77	0.73	.83	.85	1.22	1.84	0.77
1963	.61	1.36	.64	.69	.68	.72	.72	.83	.97	.89	.87	1.20	.80
1964	.62	.58	.55	.52	.62	.56	.78	.68	.94	.97	.73	.72	.68
1965	1.17	.83	.55	.52	.61	.81	.88	.81	.90	1.10	.82	.90	.79
1966	1.32	.66	.65	.82	.93	.88	.96	.77	.76	.90	.85	1.10	.86
1967	.42	.72	.27	.61	.64	.57	.59	.55	.80	.75	.94	.75	.64
1968	.66	1.04	.50	.64	.60	.54	.54	.77	.64	.60	.88	.52	.65
1969	.57	.93	.51	.46	.47	.58	.71	.71	.89	.81	1.40	2.08	.73
1970	1.57	.74	.80	.41	.75	.87	.49	.52	.67	.74	1.14	.84	.69
1971	.94	.42	.70	.46	.54	.38	.62	.64	-	-	-	-	.63 1/
Monthly and annual average of pan coefficients	0.88	0.78	0.58	0.57	0.65	0.67	0.71	0.70	0.83	0.84	1.00	1.09	0.72
Standard deviation of monthly and annual values	±0.37	±0.28	±0.14	±0.13	±0.12	±0.17	±0.15	±0.10	±0.11	±0.14	±0.21	±0.50	±0.08

1/ Includes data from 1961.

Table 4.--Monthly and annual net evaporation for Lake Michie, in inches

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total for year
1961									3.21	1.58	1.23	-2.84	-
1962	-5.71	-2.00	-1.12	-1.29	3.55	1.67	1.33	-2.27	.10	1.78	-3.92	.76	-7.12
1963	-1.47	-.01	-1.50	3.62	2.43	1.05	-.05	2.89	.33	3.57	-3.65	-.34	+6.87
1964	-2.75	-3.83	.25	-1.95	3.28	1.10	.23	-.85	.43	-.98	.87	-1.79	-5.99
1965	1.18	-1.62	-2.45	-.50	3.58	-3.71	-1.28	.59	2.90	2.66	1.16	1.56	+4.07
1966	-1.54	-2.60	.96	-.28	.82	4.79	4.12	1.69	.81	.14	.06	-.86	+8.11
1967	-1.22	-1.39	.08	1.29	-.95	-2.61	-1.69	-2.28	.81	.31	1.27	-3.77	-10.15
1968	-1.[illegible]9	1.61	-1.20	.82	-1.92	3.38	-.18	5.00	3.96	-3.13	-1.01	-6.32	-.48
1969	-1.26	-1.69	-2.74	-.05	1.58	-.49	.28	-.06	-.07	.59	2.62	.23	-1.06
1970	.80	-1.79	-4.92	-.52	1.85	4.27	-3.47	.09	3.55	-.22	-.84	-.27	-1.47
1971	-1.11	-3.41	-.31	-.12	-3.00	.85	.70	.23	-	-	-	-	-2.99[1]
Monthly and annual average of net evaporation	-1.46	-1.67	-1.30	+0.10	+1.12	+1.03	0	+0.50	+1.60	+0.63	-0.22	-1.36	-1.02
Standard deviation of monthly and annual values	±1.89	±1.57	±1.73	±1.54	±2.35	±2.76	±2.00	±2.24	±1.60	±1.91	±2.16	±2.38	±5.97

1/ Includes data from 1961.

evaporation by that amount. During the 10 years of record, evaporation generally exceeded precipitation for the months of April through October with maximum exceedance in May and September. The exceedance is not so great in June, July, and August because of higher rainfall during those months, although the maximum net evaporation of the 10-year period (5 inches) did occur in August 1968.

The standard deviations of the monthly and annual net evaporation values are also shown in table 4. The standard deviations here are relatively large compared to simple evaporation. Therefore, prediction of future events based on monthly and annual averages is not considered advisable.

The average yearly net evaporation was -1.02 inches during the study period. This negative value reflects the fact that evaporation averaged 37.9 inches and precipitation was about 39 inches during that period. Long-term annual average precipitation is about 45 inches, and if long-term annual evaporation averages about 38 inches, then the average annual excess of precipitation over evaporation is perhaps 5-9 inches for Lake Michie.

Periods of low inflow and high evaporation rates are of major interest in lake management and development. These periods generally occur during periods of below normal rainfall. Frequency curves of net evaporation, which depict the frequency of occurrence of cumulative totals of net evaporation over various periods of consecutive-days, are shown in figure 6. For example, we can expect that the maximum net evaporation for a 183-day period (6 months) will be equal to or greater than 14.5 inches once every 20 years, on the average. These periods of maximum net evaporation tend to, but do not necessarily, coincide with periods of low streamflow. Information from these net evaporation curves can be used to estimate losses of water from storage during critical periods. Actual losses of water from storage due to evaporation during a particular critical low flow period are likely to be somewhat less than losses estimated by this method. Also, caution should be used in estimating net evaporation at the higher recurrence intervals because the part of the curve above the 10-year recurrence interval is an extension. The results, however, are useful as reconnaissance estimates.

Evaporation and Storage Requirements

In the determination of storage requirements for proposed reservoirs to meet water demands, many facets of design need to be considered, among these are the patterns of draft, the inflow characteristics, the suitability of the storage site in question, the possibility of modifying the reservoir capacity to provide for flood control or recreation, and the amount of evaporation.

A common practice in the southeast is to ignore evaporation on the grounds that, in the long run, it is about equal to precipitation. While this assumption is generally valid, evaporation during critical periods can be of

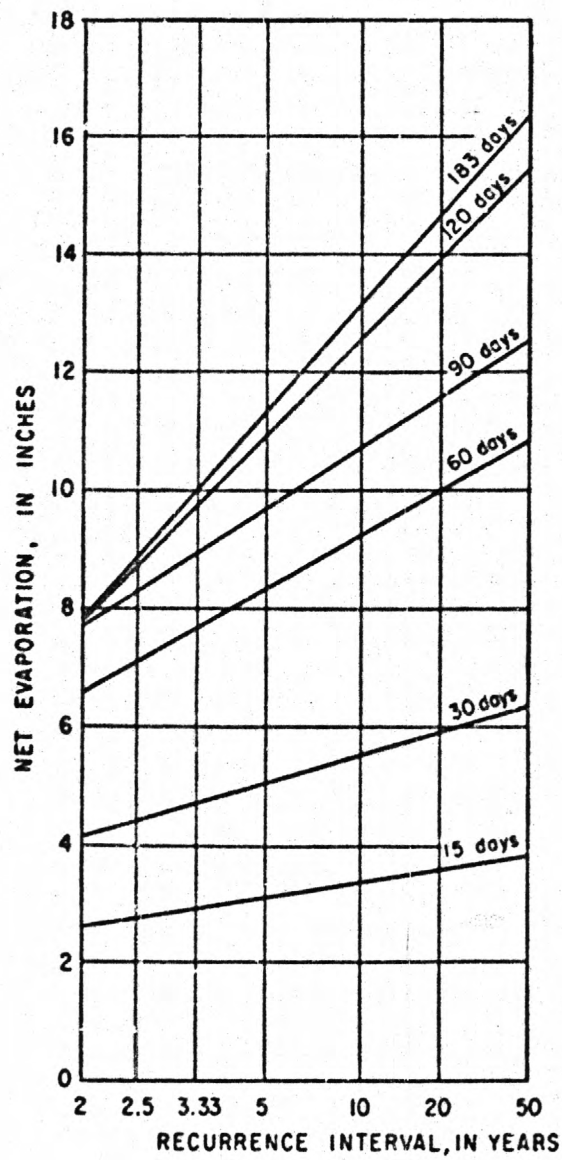


Figure 6.--Frequency of occurrence of net evaporation.

sufficient magnitude to merit closer analysis and may even affect the design of some reservoirs.

One purpose in collecting records of Lake Michie evaporation was to provide information on evaporative losses from reservoirs that can be used in design and management. We have seen from figure 6 that net evaporation can be as much as 1.4 feet on Lake Michie for critical periods of 6 months. Hubbard (written commun., 1972) devised a method by which these frequency curves of net evaporation can be used to account for evaporative losses in reservoir design. These relations are applicable, not only for Lake Michie, but for other existing or proposed reservoirs in the North Carolina Piedmont (see fig. 1) where lake surface areas and drainage areas upstream from the sites are known or can be determined.

Figures 7, 8, and 9 show the regional evaporative draft relations for 10-, 20-, and 50-year recurrence intervals. In brief, the evaporative drafts obtained from these relations represent net evaporation during critical low-flow periods and can be used in conjunction with draft-storage relations contained in other reports, including Goddard (1963) and Putnam and Lindskov (1973) or with other relations developed by similar methods.

For example, suppose it is determined that a proposed reservoir can support a draft of 3 mgd (million gallons per day), being deficient only once in 20 years. The evaporative losses must be deducted from this draft. If the lake has a surface area of 300 acres and the area draining into the lake is 100 square miles, then from figure 8 the evaporative loss is determined to be about 0.5 mgd. This loss occurs during the critical period on which the 3 mgd yield is based. Thus, the reservoir will only supply 2.5 mgd to the user during this period because 0.5 mgd is lost to evaporation. This correction may or may not be significant for a particular storage project. The purpose here is to provide a simple means to quantify evaporative losses so they may be considered if they are significant. The relations shown in figures 7, 8, and 9 have been reduced to equations along with relations for 10-, 20-, and 50-year recurrence intervals. These are:

$$E = 0.00233\ D^{0.20509} S^{0.77149} \quad \text{(10-year recurrence interval)} \qquad (5)$$

$$E = 0.00232\ D^{0.19726} S^{0.78882} \quad \text{(20-year recurrence interval)} \qquad (6)$$

$$E = 0.00241\ D^{0.18202} S^{0.79806} \quad \text{(50-year recurrence interval)} \qquad (7)$$

where D is drainage area, in square miles, S is surface area in acres, and E is evaporative draft in million gallons per day.

An error analysis showed that the standard error of estimate in evaporative draft from these relationships was no more than about 4 percent for the 10-year recurrence interval, 9 percent for the 20-year recurrence interval, and 9.5 percent for the 50-year recurrence interval. We assumed that the frequency curves of net evaporation for Lake Michie are correct and that they apply also to other areas of the Piedmont in North Carolina. We also assumed that periods

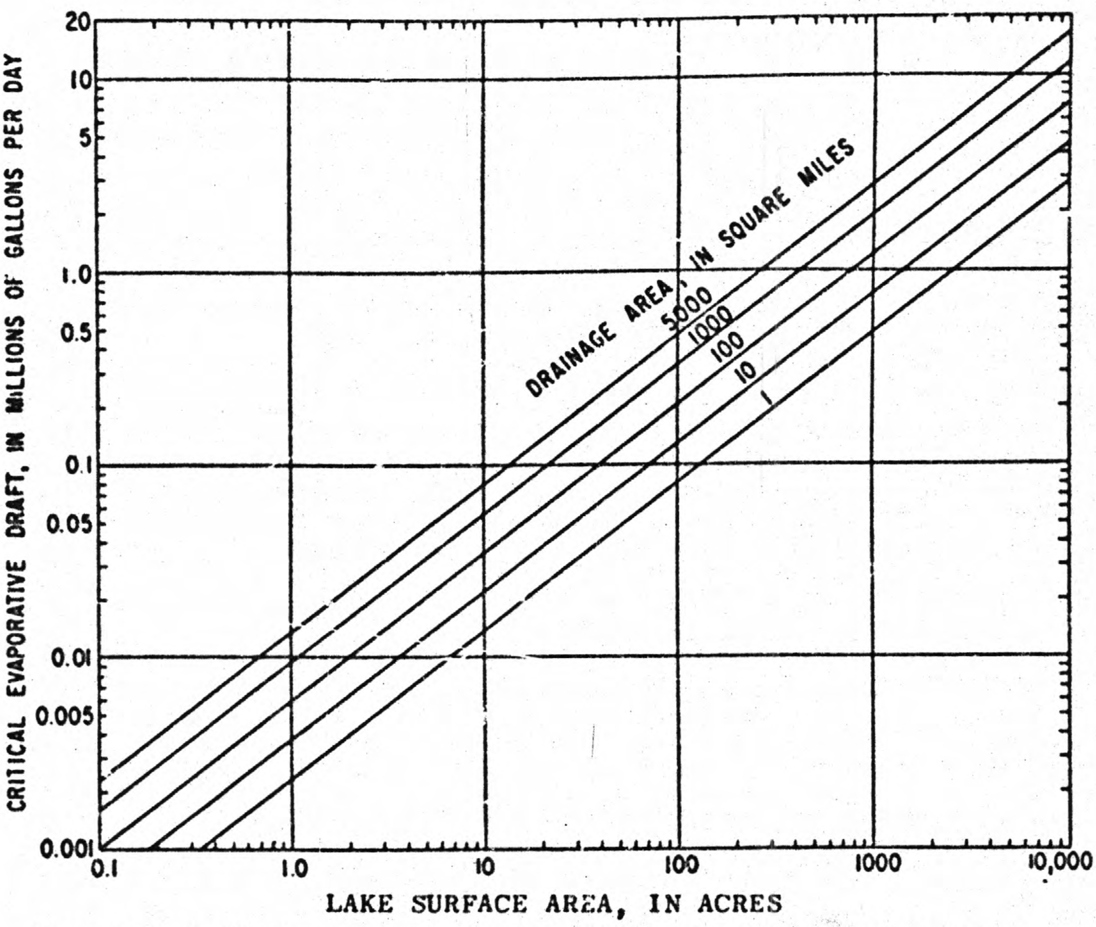


Figure 7.--Regionalized evaporative draft relationships for the Piedmont area for a 10-year recurrence interval.

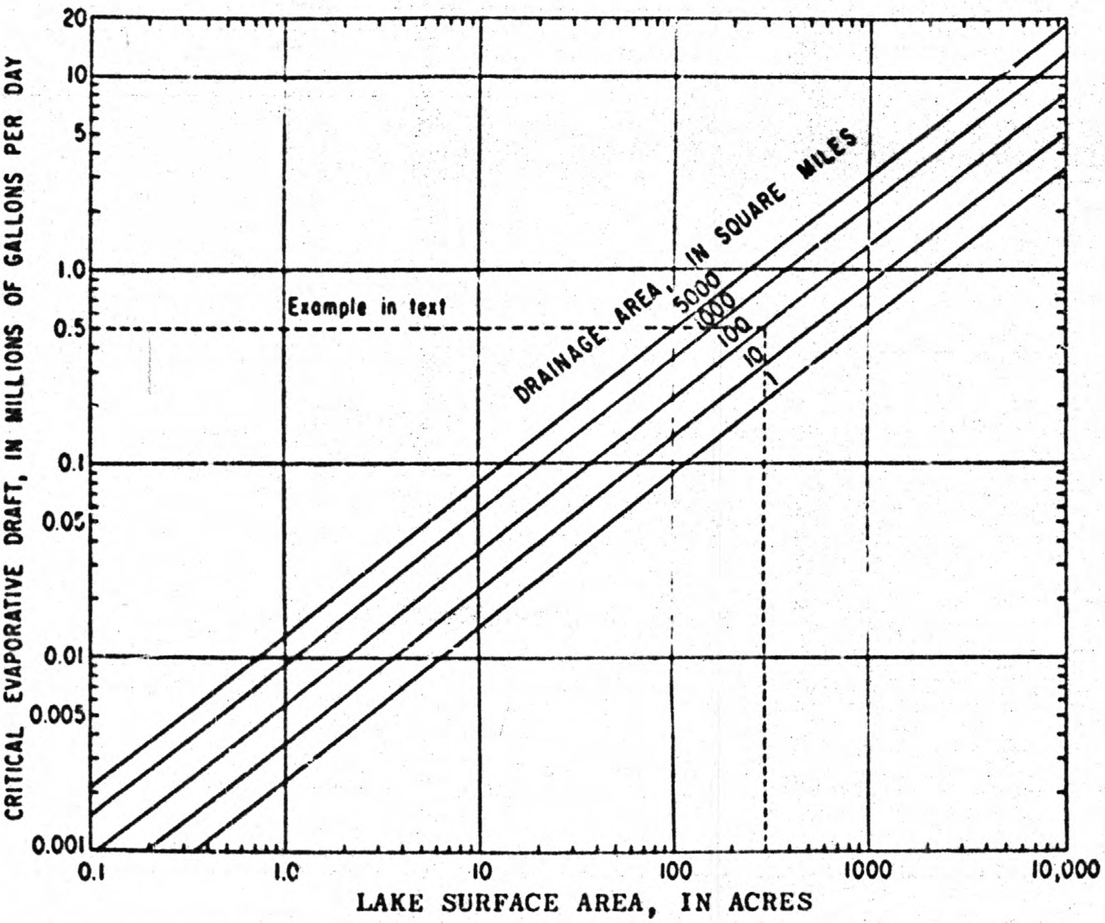


Figure 8.--Regionalized evaporative draft relationships for the Piedmont area for a 20-year recurrence interval.

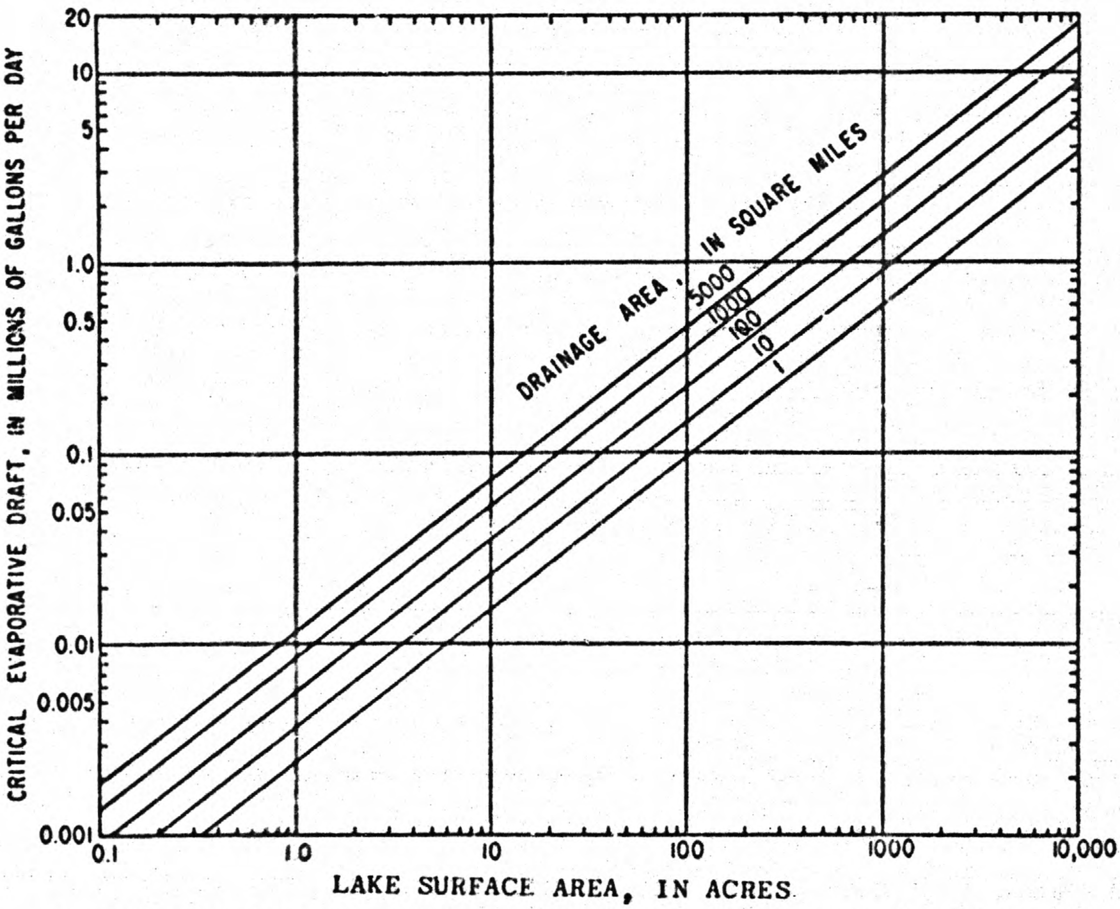


Figure 9.--Regionalized evaporative draft relationship for the Piedmont area for a 50-year recurrence interval.

of high net evaporation coincide in time with periods of low flow of the same ranking. This second assumption tends to be true because high net evaporation and low streamflow both occur during periods of low precipitation. Errors introduced through this assumption would result in slightly higher estimates of evaporative draft than will have actually occurred, and, therefore, are safer for purposes of design and management. It is important to note that evaporative drafts given by these relationships apply only to the critical 10-, 20-, and 50-year maximums upon which the reservoir designs are based. Average monthly and annual net evaporation rates should be estimated from table 4.

Although it was not a direct objective of this study to evaluate the overall adequacy of the Lake Michie water-supply system, it is useful to note that under present operating conditions, excess storage in Lake Michie is more than enough to compensate for any conceivable evaporative losses. However, if present draft rates were increased to 30 mgd, there would be a temporary deficiency in draft once in 20 years, on the average. At such a stage of development, evaporative losses would have to be considered carefully.

ERRORS

The tables of evaporation, the frequency curves, and the evaporative draft relationships in this report contain errors due to imprecise or inaccurate measurements of the climatological and hydrographic variables upon which the calculations are based. The errors in measurement of individual variables, when combined mathematically with other variables, lead to some resultant error at the end of the computational chain. This resultant error may be larger than, or smaller than, any of the errors in the individual variables, depending on how the variables are combined. In addition, when we consider the ten year study period to be representative of future events, there is some error or uncertainty in this assumption. Although a complete mathematical analysis of errors in this study would be difficult, if not impossible, it is well worthwhile to discuss the major specific sources of error and their probable effects.

With regard to meteorological data, for instance, errors of as much as 25 percent could be introduced in the term $\mu(e_o - e_a)$ in equation 3 if the corresponding average daily temperatures T_o and T_a were in error by 2°F. Because of this, care was taken to correct recorded daily temperatures to a reference thermometer, so that errors are random and noncumulative and thus have a small effect on average values computed from seven or more days of record. Such errors that remain in the term $\mu(e_o - e_a)$ are to a large extent compensating and "average out" in the final calibration of figure 3. The location of the instrument raft also affects the accuracy of calculations of the calibration. Care was taken to locate the instrument raft at a place representative of average wind velocities and water temperatures, but some sampling error is doubtless present, particularly in wind velocities. Again, many of these are compensating errors, but there may be some seasonal bias in the final calibration curve.

Errors in the ΔH_A term in equation 3 are caused by errors in measuring inflow and outflow, in the stage-area relation for Lake Michie, in pumpage and stage records, and by variations in net seepage. Turner (1966, p. 144) reports that an error as high as 104 percent in ΔH_A for Lake Michie could be introduced by a 5 percent error in measured inflow of 27 cfs. These and other errors were minimized by careful selection of calibration time periods where accuracy could be maximum. Again, the sum of these errors results in random errors in the calibration points. However, the average curve is well defined through most of its range, making possible estimates of evaporation within acceptable limits of accuracy. The evaporation data generated at Lake Michie appears very reasonable on a yearly basis when compared with what might be generated from pan evaporation data and other techniques. There is good cause to believe, therefore, that the monthly values in table 2 are also reasonable.

The tables of net evaporation are subject to more percentage error than simple evaporation because of the small differences that result from subtracting precipitation from evaporation, and these errors are of course incorporated in the frequency curves of net evaporation. Here again, many of the errors in the daily calculations are random and total out over the month.

With regard to net frequency curves, there is some additional uncertainty because of the inherent assumption in them that the 10-year study period was representative of future events. Because of this, care would be exercised in use of net evaporation values from the higher recurrence intervals. Nevertheless, use of these curves should give acceptable results for most studies.

Errors from the frequency curves of net evaporation are, in turn, incorporated into the evaporative draft relationships. The additional standard error due to the manner of construction of the evaporative draft relations is no more than 9.5 percent for the 50-year recurrence interval; and is less for the 20- and 10-year intervals. Although these additional errors are quite acceptable in themselves, the total error involved in the estimates of evaporative drafts may be considerably larger. Therefore, use of these particular relations is limited to reconnaissance studies.

SUMMARY

Average annual evaporation from Lake Michie was 37.9 inches for 1961-71, as determined by the mass-transfer water-budget technique. Because evaporation varies primarily with solar radiation in a stable annual cycle, the 10-year record was of sufficient length to accurately define long-term annual and monthly values. Maximum monthly lake evaporation usually occurs in July, and

averages 4.71 inches for that month. Minimum monthly evaporation usually occurs in January, and averages 1.45 inches.

The average annual pan coefficient for Lake Michie of 0.72 is similar to coefficients obtained elsewhere in the southeast, and can be used to estimate annual lake evaporation elsewhere in North Carolina where nearby pan evaporation data are available. The average monthly pan coefficients may also give acceptable results for some purposes, although the confidence intervals are greater than those for the average annual pan coefficients.

Net evaporation for Lake Michie during 1961-71 was -10.2 ~~-1.02~~ inches; that is, precipitation exceeded evaporation by that amount over the entire study period. Occasionally, however, evaporation was significantly greater than precipitation, and frequency studies indicate that over 16 inches of net evaporation may occur during a 6-month period once every 50 years, on the average. Such periods of high net evaporation rates are likely to occur at times of very low streamflow, creating critical water-supply conditions in some reservoirs. On Lake Michie, however, evaporation losses are not a critical factor at the present stage of development. If withdrawal rates were increased to 30 mgd, however, a deficiency in draft would occur at an average recurrence interval of 20 years.

The regionalized relations for evaporative losses from proposed or existing lakes and reservoirs in North Carolina's Piedmont region can be used in management and planning for future water-supply projects. The common assumption that evaporation losses are cancelled by precipitation is only valid for long time periods, and not for the short or critical periods upon which reservoir designs are based.

SELECTED REFERENCES

Dixon, W. J., and Massey, F. J., Jr., 1951, Introduction to statistical analysis: New York, McGraw-Hill, 370 p.

Goddard, G. C., 1963, Water-supply characteristics of North Carolina streams: U.S. Geol. Survey Water-Supply Paper 1761, 223 p.

Harbeck, G. E., Jr., 1952, Evaporation research at Lake Hefner: Am. Water Works Assoc. Jour., v. 44, no. 8, p. 701-706.

_______ 1962, A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory: U.S. Geol. Survey Prof. Paper 272-E, p. 101-105.

Harbeck, G. E., Jr., Kohler, M. A., Koberg, G. E., and others, 1958, Water-los investigations - Lake Mead studies: U.S. Geol. Survey Prof. Paper 298, 100 p.

Linsley, R. K., Jr., Kohler, M. A., and Paulhus, J. L. H., 1958, Hydrology for engineers: New York, McGraw-Hill, 340 p.

Marciano, J. J., and Harbeck, G. E., 1954, Mass-transfer studies, in Water-loss investigations - Lake Hefner studies, technical report: U.S. Geol. Survey Prof. Paper 269, p. 46-70.

Putnam, A. L., and Lindskov, K. L., 1973, Water resources of the upper Neuse River basin, North Carolina: U.S. Geol. Survey Water-Resources Inv. 12-73, 68 p.

Turner, J. F., Jr., 1966, Evaporation study in a humid region, Lake Michie, North Carolina: U.S. Geol. Survey Prof. Paper 272-G, p. 137-150.

☆ G. P. O. 1973 — 744-278 / 608. REGION NO. 4

END

DATE

FILMED

12-13-74

NTIS